Haptic Motion: Improving Sensation of Self-Motion in Virtual Worlds with Force Feedback

Nizar Ouarti[*] — Université Pierre et Marie Curie (Paris VI) / CNRS

Anatole Lécuyer[†] — INRIA

Alain Berthoz[‡] — College de France

Abstract

Haptic feedbacks are usually used to provide a sensation of interaction with virtual or distant objects. These feedbacks give an access to the physical properties or constraints of these objects in a given environment. In the present study, we wondered if a haptic feedback in the hands can provide an enhanced sensation of whole-body self-motion in virtual worlds. We designed two experiments where subjects were visually immersed in a moving virtual environment and exposed, in parallel, to a force feedback stimulation in hands coherent with the virtual camera motion. In the first experiment, the motion was in a straight line combined with a force feedback acting only on Z-axis (longitudinal) and with an amplitude proportional to the acceleration of the virtual camera. We showed that the visuo-haptic stimulation produces a higher sensation of self-motion compared to the visual feedback alone. In the second experiment, we tested our method with a more complex virtual camera trajectory, inducing an acceleration vector of the virtual camera owning components in each 3D axis. Based on the difference of orientation between the velocity and acceleration vectors of the camera, we showed that the force feedback, providing the most important sensation of self-motion, has the same 3D orientation and is proportional in magnitude to the acceleration of the virtual camera. These results highlight the way visual and haptic cues interact together to provide a self-motion sensation. Taken together our results suggest new applications of force-feedback devices in VR, for the purpose of enhancing self-motion sensations.

Keywords: Self-motion, Haptic Feedback, Vection, Multimodal.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—[artificial, augmented, and virtual realities]; H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces—[Haptic I/O]; H.1.2 [INFORMATI0N SYSTEMS]: User/Machine Systems—[Human factors, Human information processing Design, Experimentation, Human Factors, Performance]

1 Introduction

Virtual reality technologies target high degree of spatial presence. When the virtual scene is in displacement, meaning that the point of view of the user is supposed to move, it is sometimes critical to provide to the user the corresponding inertial cues and/or the sensation of self-motion. In this work we introduce a method based on visuo-haptic stimulation that improves the sensation of self-motion and which brings many benefits compared to other techniques. The originality of the technique is to use haptic force-feedback. Forces are applied on the hands of the user synchronously and consistently with the visually perceived motion.

Sensation of self-motion is a multimodal perception. It means that many sensorial channels are combined to give a unique sensation of self-motion [19]. These sensorial channels can be visual [22, 2, 29] tactile [32, 33], proprioceptive [17], vestibular [2] and even auditory [18]. A taxonomy of self-motion cues is proposed here, based on the physiological substrate mainly targeted, in four main categories: visual, vestibular, tactile and proprioceptive cues.

The most frequent manner to immerse people in a virtual world is to use visual cues alone. For instance, watching a large screen or wearing a head mounted display that covers the most important part of the field of view, is classical in virtual reality systems. This kind of technology can induce spatial presence and one of its components can be vection. Vection is a well-known illusion of self-motion. Most people have experienced at least one time, in a train, a visually induced illusion of self-motion, caused by the optic flow of another train, observed by the window, which starts. In this situation people have the sensation of moving in the direction opposite to the optic flow although they are steady. Vection can be circular (i.e. generated by a rotational optic flow) or linear (generated by a linear optic flow) [2, 23, 12, 29]. However, visually induced self-motion is limited as vision is well adapted to detect velocity information but not acceleration [23]. This means that some other cues can be useful to enhance the sensation of self-motion and thus spatial presence. In this study we propose an approach using vision and haptic cues to induce an illusion of self-motion.

2 Related work

A solution to provide self-motion cues in virtual environment is vestibular stimulation [9]. We can quote three major types of stimulation: hexapod, rail-based devices and galvanic stimulation. Stewart platforms (also called hexapods [26, 6]) and its variants are widely used in flight or driving simulators. The main principle underlying this technology is to move the platform in six degrees of freedom (3 rotations and 3 translations) with six hydraulic cylinders (hexapod). However, classical hexapods are very limited in term of workspace. For this reason, hexapods on rails were invented. Platforms on rails give the possibility to have a wider range of linear accelerations. Typical examples, developed for the automotive industry are the Ultimate Platform developed by Renault and the Toyota driving simulator. Galvanic stimulations are used to stimulate directly the vestibular system [14]. The principle is to send a current in the inner hear that stimulates some vestibular neurons to provide a sensation of motion [1].

The tactile system can also provide inertial cues for instance with vibrotactile actuators. The vibrotactile actuators used in current motion simulators are characterized by a narrow range of frequencies [30] or related to the sound of an engine [25]. However, a recent study shows that vibro-tactile stimulations can improve the sensation of self-motion when the frequency content is varying ([20, 8]).

Last, proprioceptive cues can also be implicated. Here, we defined proprioception as the perception of the limbs movements and limbs positions and also as the perception of the external forces exerted on the limbs. The sensory receptors involved in proprioception are principally the muscles spindles and the joints receptors [15, 31].

[*]e-mail: ouarti@isir.upmc.fr

[†]e-mail:alecuyer@inria.fr

[‡]e-mail:alain.berthoz@college-de-france.fr

IEEE Haptics Symposium 2014
23-26 February, Houston, Tx, USA
978-1-4799-3131-6/14/$31.00 ©2014 IEEE

Although, it was stated that during treadmill locomotion, there is rarely any illusion that one is actually moving forward [7], the proprioceptive cues like walking on a treadmill or pedaling on a bicycle [11] can be quoted. Because for instance, walking on circular treadmills can, however, induce circular vection rather reliably [3]. The sensation of self-motion is, here, induced by the actions of the muscles. Our new technique can be classified in this latter category.

All the technologies developed so far to generate self-motion cues in virtual environments suffer from intrinsic limitations. A first limitation concerns the necessity of specific workspace requirements for most of these devices. This problem occurs in the case of rails, multi-directional treadmills and for hexapods. This problem notably limits the access to these technologies to individual customers at home. Besides, individual customers cannot usually pay the high price inherent to such technologies. These problems limit the spreading of these technologies outside laboratories and/or large scale companies.

Another limitation that we can quote is the restricted duration of the induced perception of self-motion. For instance, it is well-known that vection is intermittent and cannot be experienced in a long time window. It means that a visual stimulation cannot provide a sensation of self-motion for a long duration. In the case of tilting device it was shown that people can distinguish between tilting (gravitational acceleration) and linear displacement (inertial acceleration) when the tilting device has an angular velocity above the threshold of semi-circular canals [27, 16]. It means that, to produce an illusion of self-motion, a tilting method can be used for long-duration acceleration but this acceleration has to come progressively, and cannot reproduce the fast variations of acceleration. A limitation on the duration of acceleration occurs with the rail technology: because of the limitation of the rails length. Furthermore, these rails and tilting platforms are also difficult to control. Complex subthreshold movements (under the threshold of perception) have to be done to remain in the workspace of the platform.

Moreover, one can often notice a lack of directionality of the existing techniques. For instance, a simple unidirectional treadmill is rather cost-efficient and does not require a large workspace. However, it provides only one direction of stimulation. This means that the subject can only feel that he moves on a straight line. This is also a current limitation of the vibrotactile devices. Galvanic stimulation suffers from the same kind of limitation. The galvanic stimulation is not specific; it stimulates randomly a population of neurons which have different directional sensitivities. No galvanic system is able to give a directional stimulation.

Last, a limitation concerns the relation between the evolution of the magnitude of the virtual acceleration and the information that can be sent. We already mentioned the intrinsic limitation of the visual system. It means that a visual device cannot give accurate information related to the change of acceleration magnitude. Vibrotactile devices also do not provide specific information related to the acceleration profile. Usually the information sent is a bit of information: motion (vibration) or no motion (no vibration). However, recent developments seems to overcome the shortcomings of vibrotactile stimulation ([20, 8]). With rail devices a relation with virtual acceleration is possible but in a very small range and during a limited time because of the limitation of the size of the rails.

We can quote few related works that explored a comparable orientation. In a psychophysical study, Mergner et col. [17] showed that it is possible to induce an illusory sensation of rotation of the head by only rotating the trunk, in the dark. This could be considered as an illusion of self-motion induced by proprioception only.

Another study related to disorientation in an aircraft showed that tactile cues can be used to control the self-motion illusion [4]. The aim of this work was to determine whether a vibrotactile stimulation of the torso of a subject who pilots an aircraft can limit the disorientation. The authors' hypothesis of a disambiguating role of vibrotactile actuators was confirmed by the results of their experiments.

A previous study by Rieke used force feedback on a modified wheelchair and found clear increase in visually induced vection[24]. But in this study the specific role of proprioceptive and vestibular cues cannot be distinguished reliably.

Here, we will focus on haptic display. Haptic stimulation can be considered to mainly give proprioceptive cues and also tactile cues to some extent. Some previous works suggest that haptic feedback can enhance the evaluation of self-motion. In a previous study, in a virtual environment, a virtual tunnel was visually displayed. The task of the subjects was to determine the angle of the tunnel's turn with (or without) a haptic device that rotated the same angle [13]. The results of the study were a not significant tendency in favor of the haptic condition to evaluate the angle turn.

In our study, we do not evaluate a virtual motion. The specific aim of our study is to enhance the sensation of self-motion in virtual worlds with a visuo-haptic stimulation.

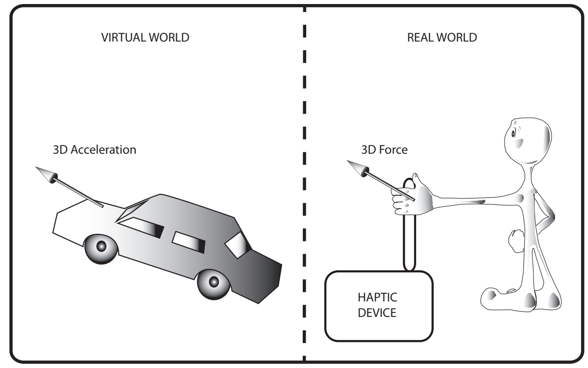

Figure 1: Visuo-Haptic Scheme: a force is sent in the hand of the user which is proportional and in the same 3D orientation than the visually perceived acceleration vector.

3 Concept

We propose a change in the usage of haptic devices. Haptic feedback has been mainly used to interact with objects in a virtual environment. Haptic devices enable to give the sensation of touching or moving objects, to feel their weight or their texture. The radical change in our concept is that haptic feedback is used to produce the illusion that the user's body is moving in the 3D space. The key idea of our approach is to send a force to the user which is proportional and in the same orientation than the inertial acceleration vector (Figure 1). Applying such force on subject's hands is expected to produce a sensation of whole-body self-motion because it is coherent with 3D visual cues [21].

Figure 2 describes the simulation pipeline that represents the implementation of our concept. A physics engine determines the virtual acceleration. The box *visual rendering* is defined here as visual information produced in parallel to haptic force-feedback. The 3D force is computed and sent synchronously with the 3D visual scene. This means that the visual scene is moving with a 3D acceleration proportional to the 3D force feedback and in the same 3D direction.

4 Experiment 1: Can force-feedback increase the illusion of self-motion?

This first Experiment can be considered as a proof of concept of our novel approach. We wanted to test whether a haptic feedback synchronized with a visual stimulation can increase the self-motion

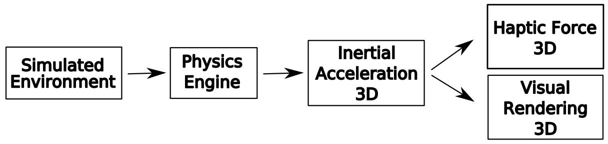

Figure 2: Simulation pipeline. Simulated environment corresponds to the virtual world that was designed and to the characteristics of the vehicle. The physics engine deduces, from the virtual world and from the initial state, the dynamic of motion of the vehicle and particularly the inertial acceleration. The Şvisual renderingŤ corresponds to the production of a 3D visual scene. ŞHaptic forceŤ corresponds to the 3D force produced by the force feedback interface.

sensation. To this aim, we designed an Experiment where, in combination to a visually displayed motion, a haptic feedback can be present or not, aiming to observe its specific effect. Usual markers of vection were collected in this experiment: the onset, the duration of illusion, the frequency of occurrences of the illusion [23, 12, 22, 29]. The modulation of these answers can quantify the change in self-motion perception.

4.1 Participants

Nine participants took part in this Experiment. They were 6 men and 3 women aged between 22 and 56 years. All participants had normal or corrected vision.

4.2 Stimuli and Apparatus

In this Experiment, virtual motion was a positive step of acceleration beginning after 3 seconds and finishing with the trial. The duration of each trial was 25 seconds to avoid visual adaptation to stimulus [10] and possible after effect [28].
The direction of the haptic stimulation was in 1 axis, longitudinal in the reference frame of the subject.
The visual scene consisted of a 3D textured cylindrical tunnel designed in OpenGL. The subject was seated at 1.30 m to the screen, and the dimensions of the screen were 1m80 vertically and 2m40 horizontally. The angle of view was 108 degrees vertically and 123 degrees horizontally. For a more realistic spatial presence, black curtains were tightened between the border of the screen and the chair.

Subjects were strapped on the chair at the level of the shoulder and the belly to avoid vestibular stimulation during the haptic stimulation (Figure 3). Indeed the effect of vestibular stimulation on linear vection is well known and is described in Pavard and Berthoz (1977) [23]. This procedure allows to test the specific impact of haptic cues on self-motion. Subjects grasped with their two hands a 6DOF haptic device (Virtuose, Haption) as illustrated in Figure 3. We asked subjects to have the thumb of their dominant hand on the haptic device button throughout the trial. This procedure ensures that the subject pushed (or released) the button exactly at the moment when the illusion of self-motion began (or disappeared). Subjects were also asked to maintain the haptic device in the same position, i.e. to resist to force feedback.

4.3 Procedure and Task

Subjects were instructed to press the button when they feel that they have an illusory sensation of motion, not when the image of the screen moves, not when the haptic device moves, but an illusory sensation of motion comparable to *the illusory sensation when a person is in a train and sees another train which starts*. They were also instructed to push the button and to keep pressing it as long as the sensation continues, to stop if the sensation disappears and also to push back the button again if the sensation restarts. After

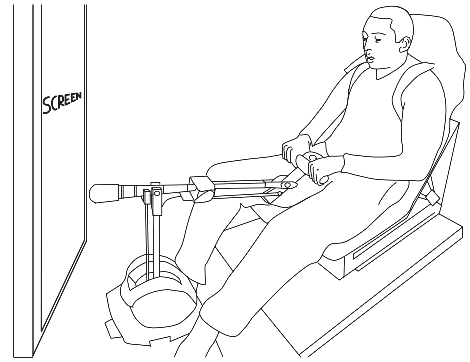

Figure 3: Experimental apparatus: subject grasping the 6DOF haptic devices. Subjects had to put the thumb of their dominant hand on the button during the trials. They grasped the haptic device with two hands in a symmetric manner. Subjects were strapped on the chair to avoid torso and head movements. Subjects were in a room in front of a large screen surrounded by curtains where they were visually immersed.

each pair of trials subjects have to judge which one gave a stronger sensation of self-motion.

4.4 Design

Three different conditions were used: haptic-only (H) condition which provides a dynamic haptic feedback but with a null optic flow field, visual-only (V) condition with a non-null optic flow field and a static force-feedback arm, and the coherent multimodal condition with motion cues coming from both haptic feedback and optic flow field (VH).

These three different conditions were presented by pair. The combination of these conditions gives 6 different pairs. These 6 pairs were randomly presented four times each. There were 24 pairs of trials making 48 trials in total.

4.5 Results

To observe the effect of haptic feedback in the different conditions, we decided to study usual markers of vection [23] [12] [22] [29]: the onset, the duration and the frequency of occurrences of the illusion. We also asked subjects to judge the sensation of motion by pair of trials. For the figures, on each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

4.5.1 Frequency of occurrences

The frequency of occurrences of the illusion of self-motion is important to compare the respective power of the different cues to give a sensation of motion. It is related to the probability to feel the illusion. All subjects felt the sensation of self-motion at least one time during the visuo-haptic condition (VH). Eight subjects out of nine felt the sensation of self-motion at least one time during the visual-only condition, the vection-like condition (V). Three subjects out of nine felt the sensation of self-motion at least one time during the haptic-only condition (H).

We compared the distribution of occurrences between the visuo-haptic condition and the other condition (see Fig.4). We used a Wilcoxson signed-rank non-parametric test and found that occurrences are significantly different when the VH condition is compared with respectively the H ($p=0.003$) and the V ($p=0.039$) conditions.

These results mean that subjects feel an illusion more often when visual and haptic feedback are present in the same time and coherently. Our results in the visual-only condition can also be compared

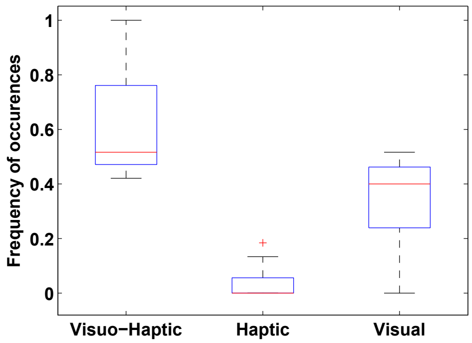

Figure 4: Frequency of occurrences of self-motion illusion in three conditions: Visuo-Haptic, Haptic-only, Visual-only. The frequency of occurrences in the Visuo-Haptic condition is higher than the frequencies of occurrences in the other conditions.

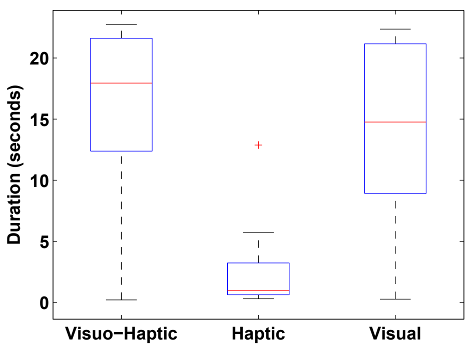

Figure 5: Duration of self-motion illusion in three conditions: Visuo-Haptic, Haptic-only, Visual-only. The duration in the Visuo-Haptic condition is significantly longer than the duration in the other conditions.

with previous studies on linear vection.
Moreover, three subjects out of nine had the feeling to move in the haptic-only condition. This surprising result suggests that the illusion of motion can be induced in some participants by haptic feedback alone.

4.5.2 Duration

The duration of illusion is also an important marker of vection. The illusion duration of self-motion is found significantly increased in the visuo-haptic condition compared with visual only (Mann-Whitney, $p = 0.013$) and haptic only (Mann-Whitney, $p = 8.4.10^{-7}$) conditions. The distribution is shown in Figure 5.

4.5.3 Onset

The onset can be defined as the duration between the beginning of stimulation and the moment when a subject perceives an illusion of self-motion. A representation of the distribution of onsets in each condition is shown in Figure 6. It can be seen that the median of the onset is lower in the haptic-only (H) condition (1.30 seconds) after comes the visuo-haptic (VH) condition (1.79 seconds) and the higher onset median occurred for the visual-only (V) condition (3.50 seconds).
The distribution of the onset did not follow a normal law. Thus, we computed a non-parametric ANOVA to test the equality of medians in the different conditions. We obtained a p-value of 2.2 10^{-4} (χ^2(2,16.83)) which implies that the medians in the different conditions are significantly different. To determine which medians are significantly different from the others we computed three different Mann-Whitney tests. For the comparison between VH condition and H condition we found a p-value of 0.041, between VH and V the p-value was $2.7 * 10^{-3}$ and between H and V the p-value was $3.5 * 10^{-4}$. This shows that each median of the three distributions are significantly different from the others. It is possible to state that the onset is significantly different in the three conditions, with a lower onset in the H condition followed by the onset in VH condition and finally the higher onset is found in the V condition. Thus, these results show that a haptic feedback can decrease the onset needed for a subject to feel an illusion of motion when combined with visual information. This can be explained by a quicker answer of the muscles spindle compared to vision sensors. It can be also observed that the variability of onsets is ranked in the same order than median values. This means that the condition where the onsets are lower are also the more concentrated and, conversely, the conditions where the onsets are higher are more spread.

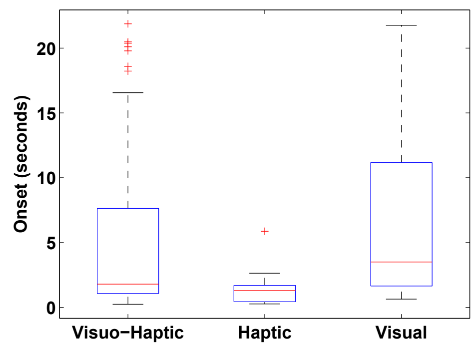

Figure 6: Onset in three conditions: Visuo-Haptic, Haptic-only and Visual-only. The Haptic-only condition has the lowest onset (concentrated around 1.30 seconds) after comes the Visuo-Haptic condition (concentrated around 1.79 seconds) and finally the Visual-only condition (more spread with a lot of onsets beginning around 3.5 seconds).

4.5.4 Subjective questionnaire

Subjects had to answer after a pair of trials whether in the second trial of the pair, the sensation of motion was superior or not compared to the first one of the pair. The results of this forced choice question are summarized in Figure 7. Subjects significantly judge that the visuo-haptic condition was the condition where they felt the most important sensation of motion, in second position comes the visual-only condition and finally the haptic-only condition.

4.6 Provisional conclusion

The haptic information has a significant influence on frequency of occurrences, duration, onset of illusion, and also on the subjective intensity of the sensation of self-motion. Given all these results, we can conclude that a haptic feedback can modify self-motion perception and enhance it. It appears that visuo-haptic condition leads to a short onset (probably due to haptic information) and a long duration (probably due to visual information).

5 Experiment 2: Generalization of the Concept in Full 3D Context

In the first experiment the simulated motion was in a straight line. We showed that a visual stimulation combined with a force feedback applied in one axis, with a force amplitude proportional to the

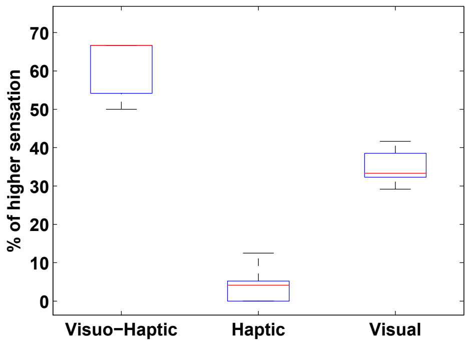

Figure 7: Percentage of subjective answers where a condition was considered to provide a greater sensation of self-motion. The Visuo-Haptic condition is judged to provide the greater sensation of self-motion compared to the other conditions.

acceleration of the virtual camera, provides a more important sensation of self-motion compared to visual stimulation alone. In the second experiment, the aim is to generalize the concept. A more complex trajectory was presented to the subjects, inducing an acceleration vector with 3D components. We wondered if a 3D force feedback having a proportional magnitude and sharing a common 3D orientation with the acceleration of the virtual camera provides the most important sensation of self-motion compared to other force feedback patterns.

To answer to this question we designed 5 haptic patterns (one pattern with no haptic force). And, subjects were asked to select the one that gives the most important sensation of self-motion in different pairs of trials. Finally, subjects had to estimate according to different subjective criteria (self-motion, spatial presence and realism) the sensation provided by the different patterns.

5.1 Participants

Eight naive participants took part in this Experiment: 4 females and 4 males aged between 21 and 42 years with a mean value of 27.88 years. All participants had normal or corrected vision.

5.2 Stimuli and Apparatus

The apparatus and the position of the subjects were similar to the previous ones of the first Experiment. The specificity of this Experiment is that we simulated a 3D environment (3D curved tunnel) and we used a physics engine to deduce the acceleration of a simulated vehicle. Subjects were exposed to a physically-based acceleration depending of the shape of the tunnel. This acceleration is based on the simulated vehicle which was subject to gravity, rails reaction, friction with the rails and with the air. The motion began after a 3 seconds countdown and finished with the trial. The duration of each trial was limited to 25 seconds.

The visual scene, which consisted of a 3D textured twisted tunnel, was designed in OpenGL. This tunnel was generated with control points which determined cubic splines by interpolation. The screen dimension, the room and the position of the subject were the same as in Experiment 1.Because of the geometry of the tunnel and the realistic physical interaction between the vehicle and the environment (gravity, friction, etc...) the vehicle started with a non-null acceleration sufficient to reach the end of the complex tunnel.

5.3 Procedure and Task

The task of the subjects was to compare two successive trials according to the sensation of self-motion. We called it the pair task.

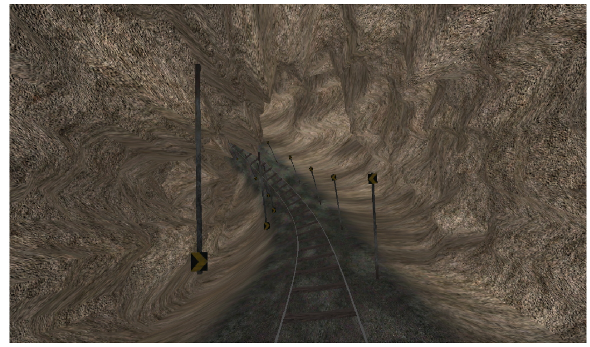

Figure 8: 3D tunnel used in Experiment 2.

At the end of each pair of trials, the subject had to push a button to continue: button 1 when he felt a stronger sensation of self-motion in the first trial and button 2 otherwise (i.e. forced choice). At the end of the 80 trials, we presented again the five different haptic patterns.

The subject was then asked to mark these five haptic patterns by giving a grade between 1 and 7, for 3 different criteria. We called it the mark task. The first criterion was the sensation of self-motion: illusion to move relatively to the environment. The second criterion was spatial presence: the sensation to be inside the virtual scene. The third creterion was realism: sensation to have a real interaction.

5.4 Design

Given the acceleration of the simulated vehicle computed in the environment, two kinds of information were computed: visual and haptic feedback. The virtual camera was attached to the vehicle. The optic flow field corresponded exactly to the motion of the vehicle. In this Experiment, the optic flow field is always identical in all conditions. The *visual velocity* is defined as the velocity that can be perceived with visual cues. For the haptic feedback, there are 5 conditions corresponding to five 3D force computations: haptic force proportional to the 3D virtual acceleration and in the same direction (HAS), haptic force proportional to the 3D visual acceleration and in the opposite direction (HAO), haptic force proportional to the 3D visual velocity and in the same direction (HVS), haptic force proportional to the 3D visual velocity and in the opposite direction (HVO) and finally no haptic feedback (NO). These five different conditions were presented by pair. The combination of these conditions gives 10 different pairs. These 10 pairs were randomly presented four times each. There were 40 pairs of trials, 80 trials in total. These pairs are randomly shuffled.

5.5 Results

To further understand what kind of haptic information is important to produce the sensation of self-motion, we asked subjects to judge the sensation of motion by pair of trials. They were 4 different haptic conditions, and one condition without haptic feedback. In each trial, subjects were in front of the screen, grasping the haptic device. After the 80 trials subjects had to mark the four different haptic feedback according to different subjective criteria: sensation of self-motion, spatial presence and realism.

We found a significant effect of the haptic feedback on the perception of self-motion. A statistical test for the pair task (kruskall wallis $p = 2.6\ 10^{-6}$) shows that there is a significant difference between conditions (Figure 9). To characterize these differences we used a posthoc test. This test shows a difference between all the conditions compared to the NO condition (Mann-Whitney, $p = 1.5\ 10^{-4}$,$p = 3.1\ 10^{-4}$,$p = 9.6\ 10^{-4}$, except for the condition HVS compared with (NO) (p = 0.053) which is very close to the limit, suggesting that haptic feedback proportional to acceleration have a clear effect on self-motion perception but for haptic feedback proportional to velocity, the effect seems to be weaker. This statistical test also showed that there is a significant difference between HAS and HAO compared respectively to HVS and HVO (Mann-Whitney, $p = 1.5\ 10^{-4}$, $p = 3.1\ 10^{-4}$, $p = 1.5\ 10^{-4}$, $p = 7.8\ 10^{-4}$) meaning that the haptic feedback proportional to acceleration provides a more important sensation of motion compared to the haptic feedback proportional to velocity. Moreover the statistical test showed that the preferred direction of stimulation is randomly distributed among subjects for the haptic feedback proportional to the acceleration (Mann-Whitney, $p = 0.24$). But for the haptic feedback proportional to the velocity the opposite direction provides a more important sensation of motion (Mann-Whitney, $p = 0.030$).

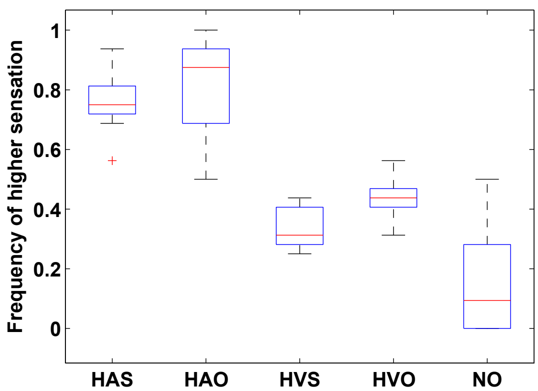

Figure 9: Percentage of times a condition was considered to give a stronger sensation of self-motion than the others. Condition HAS: haptic feedback proportional to visual acceleration and in the same direction, Condition HAO: haptic feedback proportional to visual acceleration and in the opposite direction, Condition HVS: haptic feedback proportional to visual velocity and in the same direction, Condition HVO: haptic feedback proportional to visual velocity and in the opposite direction, and Condition NO: no haptic feedback.

The result of the mark task is consistent with the former responses in the pair task. Indeed, the acceleration profiles are always ranked first whatever the criterion: self-motion, spatial presence or realism (Figure 10, 11 and 12). We performed a statistical test to analyze whether the conditions have an influence on sensation of self-motion, spatial presence and realism (Figure 10, 11 and 12). We found a significant difference for the criterion self-motion (kruskall wallis $p = 4.1\ 10^{-6}$) when all the conditions are compared. For the spatial presence criterion the difference is also found significant (kruskall wallis $p = 4.1\ 10^{-4}$), and the same was observed for the realism criterion (kruskall wallis $p = 1.0\ 10^{-3}$). These results show that there is an effect of haptic feedback on sensation of self-motion, spatial presence and realism of the virtual world.

To further understand the kind of effect that the haptic feedback produces, we computed a posthoc test. The results are summarized in the Table 1 for self-motion, for spatial presence and for realism. It can be observed for the self-motion criterion, that there is significant differences between conditions for all comparisons except between HAS and HAO and HVS and HVO, meaning that the direction is randomly preferred by the subjects.

For the spatial presence criterion, there is a significant difference

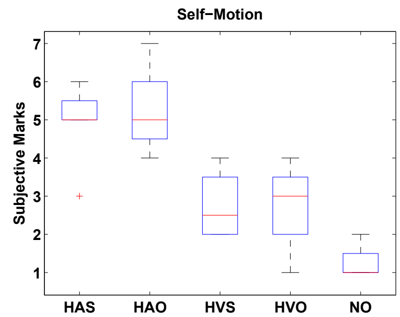

Figure 10: Subjectives preferences: Marks given for various criteria: sensation of self-motion, spatial presence and realism in the 5 conditions. Condition HAS: haptic feedback proportional to visual acceleration and in the same direction, Conditions HAO: haptic feedback proportional to visual acceleration and in the opposite direction, Condition HVS: haptic feedback proportional to visual velocity and in the same direction, Condition HVO: haptic feedback proportional to visual velocity and in the opposite direction, and Condition NO: no haptic feedback.

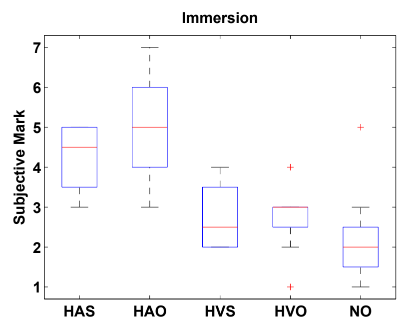

Figure 11: Subjectives preferences: Marks given for the criterion: spatial presence, in the 5 conditions (HAS, HAO, HVS, HVO and NO).

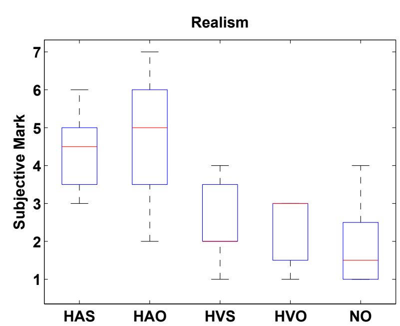

Figure 12: Subjectives preferences: Marks given for the criterion: realism, in the 5 conditions (HAS, HAO, HVS, HVO and NO).

Table 1:
Comparison of the marks for the criterion 'Self-Motion' between all the conditions (Mann-Whitney p-value.).

	HAS	HAO	HVS	HVO	NO
HAS	-	0.2606	0.0132	0.0112	0.0082
HA0	-	-	0.0037	0.0030	0.0019
HVS	-	-	-	0.8260	0.2420
HVO	-	-	-	-	0.1546
NO	-	-	-	-	-

Table 2:
Comparison of the marks for the criterion 'spatial presence' between all the conditions (Mann-Whitney p-value.).

	HAS	HAO	HVS	HVO	NO
HAS	-	0.2606	0.0132	0.0112	0.0082
HA0	-	-	0.0037	0.0030	0.0019
HVS	-	-	-	0.8260	0.2420
HVO	-	-	-	-	0.1546
NO	-	-	-	-	-

Table 3:
Comparison of the marks for the criterion 'Realism' between all the conditions (Mann-Whitney p-value.).

	HAS	HAO	HVS	HVO	NO
HAS	-	0.4406	0.0087	0.0033	0.0022
HAO	-	-	0.0172	0.0315	0.0042
HVS	-	-	-	1.0000	0.2514
HVO	-	-	-	-	0.2821
NO	-	-	-	-	-

between conditions for all comparisons except between HAO and HVS (results are comparable to the self-motion criterion), but there is also no significant difference between the two conditions HVS and HVO and the condition NO, meaning that, for this criterion, the haptic feedback proportional to velocity does not seem to add a value compared to no haptic feedback condition. The same result was obtained for the criterion realism: significant differences between conditions for all comparisons except between conditions having opposite directions. And also for this criterion, the haptic feedback proportional to velocity does not seem to add a value compared to no haptic feedback.

5.6 Provisional conclusion

With a complex virtual motion in 3D, haptic feedback based on acceleration had a more important effect on self-motion perception combined with a visual feedback. When this haptic feedback is proportional to velocity, a small effect can be noticed and it was shown that the sensation of self-motion is lower compared to the haptic feedback related to acceleration, but for the self-motion sensation the haptic feedback related to velocity have a more important effect than the case with no haptic feedback. In the case of criterion like realism or spatial presence in the 3D scene, the haptic feedback related to velocity can be considered to have no effect (i.e. comparable to the no haptic feedback condition). Last, the haptic feedback with opposite and same direction than visual motion are globally considered equivalent, in the distribution of answer. In fact, it can be observed that 50% of subjects preferred one direction and 50% preferred the other direction.

6 Discussion

We have presented a visuo-haptic effect that induces an illusion of self-motion. We showed that a combination of an optic flow together with a force feedback in the hands provides a more important sensation of whole-body self-motion, compared to optic flow alone. More specifically, we showed that when the 3D force feedback is proportional in magnitude and shares a common orientation with the acceleration of the virtual camera, the sensation of self-motion is enhanced.

We showed in the first experiment that the haptic feedback induces an enhancement of the frequency of occurrence and the duration of the illusion. The haptic feedback also decreases the onset (time needed to induce the illusion) and provides a more important subjective sensation of self-motion. This visuo-haptic illusion takes advantage of the intrinsic properties of the visual system (duration of illusion) and the haptic system (short onset). In the second experiment, the haptic feedback proportional to visual acceleration appeared to induce a more important sensation of self-motion compared to haptic feedback related to velocity. This result was confirmed for different criteria (self-motion, spatial presence and realism). Moreover, the haptic feedback proportional to velocity have a small effect on self-motion and seem to have an effect comparable to no haptic feedback considering the criteria realism and spatial presence.

Our specific apparatus warrants some discussion. First, we strapped the shoulders of users to ensure that the effect is not vestibular. Indeed, the motion was not transmitted to the body and the head but localized in the arms. This allows to claim that we do not replicate some older results, because the effect of vestibular input in the sensation of self-motion is well-known [2, 23]. On the contrary, this observation has some practical advantages. The most important one is the possibility to give the illusion only by stimulating the hand and the arm. This is important because it means that the illusion is possible with relatively small electrical engines. And it opens the possibility to have individual applications at home. In the same way this also ensures that the technology can be used in a small area and with a relative safety. And finally, the effect is not related to the entire posture, one is not supposed to stand to perceive the effect.

One of the main advantages of our technique is the ability to produce a sensation of acceleration during a long time. An ecological approach can suggest that sensing acceleration is very important for every animals including human being. Indeed, equilibrium has to be ensured in everyday life. To this end, it is very important for the central nervous system to be able to estimate the acceleration, compared to velocity for instance. It is the reason why humans are very sensitive to acceleration. To produce more immersive devices, it is critical to be able to provide a sensation of acceleration. Some other devices succeed to give this sensation like hexapods or rails but they are limited in duration of acceleration. In our case we can theoretically give a sensation of acceleration during a long time and with an important amplitude. It is the principal interest of our technique.
Another interest is the full 3D stimulation opened by this technology. There is no limitation in the orientation of stimulation with our effect. Theoretically, with our method, there is no limitation to give a sensation of self-motion in each direction of the 3D space, for instance in the Y-axis (upward direction). With usual simulators technologies, this is not possible.

The explanation of our effect can be understood by a physically coherent multimodal process. The self-motion perception is particularly multimodal. In this study, we used two modalities, proprioceptive and visual, rather than only the visual one. The result is to induce, in the brain, a more realistic sensation of self-motion. We also designed a force feedback profile that is physically coherent with the optic flow perceived by the observer. Indeed, if we consider the observer as co-located with the virtual camera, the force acting on this camera would be in the same orientation and with an amplitude proportional to the acceleration of the camera. This is warranted by the fundamental law of dynamics. But depending of the "physical interaction" with the vehicle represented by the motion of the camera, the force could be in a direction or in the opposite.
An important result of our Experiments is that subject found more realistic to have a force feedback proportional to acceleration. But the question of the direction of the 3D force vector has to be discussed. Indeed some subjects found more realistic when the force

was in the direction of acceleration and, some others, in the opposite direction. Actually, a passenger who is in a vehicle can sense two kinds of force. Based on his interaction with the vehicle, the passenger can sense forces based on inertia or pulling force. The subject can feel that he moves with the vehicle (pulled by it) or that he moves relatively to the vehicle with inertia against it. As an example when a subject stands in a train with no possibility to catch something with his hands. After an acceleration of the train, the standing subject is faced to a virtual force (inertia) that "pushes" him in a direction opposite to the direction of acceleration. In another case, a person that moves using waterskiing is pulled and the perceived force is in the same direction than the vehicle acceleration. In these two cases the sensation of self-motion is important even if the physical manifestation is slightly different. In the Experiments, we did not tried to influence the subject by suggesting the kind of interaction the subject can have in the virtual environment. Thus, the two kinds of interaction model were left possible. It is interesting that given this equiprobability of interaction models, exactly fifty percent of people were more sensitive two one direction and the other fifty percent to the other direction of force stimulation. Future work could now focus on the technical ways to suggest one interaction model or the other.

7 Conclusion

We presented a new visuo-haptic effect that induces an important sensation of self-motion only by stimulation of the hands coherent with the visual stimulation. We showed that the pattern of the haptic force is important and has to be physically coherent to be more influential. We designed specific experiments that highlight the way visual and haptic cues interact together to provide a self-motion sensation. We discussed, here, the numerous advantages of this effect and the possible technologic application. For instance, a possible application is driving simulator. Another type of application is to enhance audiovisual experience [5]. We believe that this technology can have a powerful impact on entertainment industry and any other field implying motion and navigation in virtual worlds.

References

[1] S. G. T. Balter, M. H. Castelijns, R. J. Stokroos, and H. Kingma. Galvanic-induced body sway in vestibular schwannoma patients: evidence for stimulation of the central vestibular system. *Acta Otolaryngol*, 124(9):1015–1021, Nov 2004.

[2] A. Berthoz, B. Pavard, and L. R. Young. Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. *Exp Brain Res*, 23(5):471–489, Nov 1975.

[3] W. Bles. *Attention and performance IX.*, chapter Stepping around: circular vection and Coriolis effects., pages 47–61. Erlbaum, Hillsdale, NJ, 1981.

[4] J. E. Bos, J. van Erp, E. L. Groen, and H.-J. van Veen. Vestibulo-tactile interactions regarding motion perception and eye movements in yaw. *J Vestib Res*, 15(3):149–160, 2005.

[5] F. Danieau, A. Lecuyer, P. Guillotel, J. Fleureau, N. Mollet, and M. Christie. Enhancing audiovisual experience with haptic feedback: a survey on hav. *IEEE Transactions on Haptics*, 2012.

[6] B. Dasgupta and T. Mruthyunjaya. The stewart platform manipulator: a review. *Mechanism and Machine Theory*, 35(1):15–40, 2000.

[7] F. H. Durgin, A. Pelah, L. F. Fox, J. Lewis, R. Kane, and K. A. Walley. Self-motion perception during locomotor recalibration: more than meets the eye. *J Exp Psychol Hum Percept Perform*, 31(3):398–419, Jun 2005.

[8] I. Farkhatdinov, N. Ouarti, and V. Hayward. Vibrotactile inputs to the feet can modulate vection. In *Proceedings of the IEEE World Haptics Conference 2013. Pages 677-681.*, 2013.

[9] L. R. Harris, M. Jenkin, and D. C. Zikovitz. Visual and non-visual cues in the perception of linear self-motion. *Experimental Brain Research*, 135:12–21, Nov 2000.

[10] M. A. Hietanen, N. A. Crowder, and M. R. Ibbotson. Differential changes in human perception of speed due to motion adaptation. *J Vis*, 8(11):6.1–610, 2008.

[11] J. Hollerbach. *Handbook of Virtual Environments Technology*, chapter Locomotion Interfaces, pages 239–254. 2002.

[12] J. Huang and L. R. Young. Sensation of rotation about a vertical axis with a fixed visual field in different illuminations and in the dark. *Exp Brain Res*, 41(2):172–183, 1981.

[13] A. Lécuyer, M. Vidal, O. Joly, C. Mégard, and A. Berthoz. Can haptic feedback improve the perception of self-motion in virtual reality? Chicago, 2004. 12th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (Haptics Symposium).

[14] T. Maeda, H. Ando, T. Amemiya, N. Nagaya, M. Sugimoto, and M. Inami. Shaking the world: Galvanic vestibular stimulation as a novel sensation interface. In *Proc. of ACM SIGGRAPH 2005 Emerging Technologies, p.17, L.A., CA.*, 2005.

[15] D. I. McCloskey. Kinesthetic sensibility. *Physiol Rev*, 58(4):763–820, Oct 1978.

[16] D. M. Merfeld. Rotation otolith tilt-translation reinterpretation (rottr) hypothesis: a new hypothesis to explain neurovestibular spaceflight adaptation. *J Vestib Res*, 13(4-6):309–320, 2003.

[17] T. Mergner, C. Siebold, G. Schweigart, and W. Becker. Human perception of horizontal trunk and head rotation in space during vestibular and neck stimulation. *Exp Brain Res*, 85(2):389–404, 1991.

[18] C. Muller, P. Schnider, A. Persterer, M. Opitz, M. V. Nefjodova, and M. Berger. Applied psychoacoustics in space flight. *Wien.Med.Wochenschr.*, 143:633–635, 1993.

[19] N. Ouarti and A. Berthoz. Multimodal fusion in self-motion perception using wavelets and quaternions. In *Deuxieme conference francaise de Neurosciences Computationnelles, Neurocomp*, 2008.

[20] N. Ouarti and V. Hayward. Specific vibrotactile signals in the feet enhance the experience of self-motion. In *Theo Murphy Meeting on Active touch sensing, Royal Society*, 2011.

[21] N. Ouarti, A. Lecuyer, and A. Berthoz. Haptic motion simulator: Improved sensation of motion in virtual worlds with force feedback. In *JVRC (Joint Virtual Reality Conference)*, 2010.

[22] S. Palmisano. Perceiving self-motion in depth: the role of stereoscopic motion and changing-size cues. *Percept Psychophys*, 58(8):1168–1176, Nov 1996.

[23] B. Pavard and A. Berthoz. Linear acceleration modifies the perceived velocity of a moving visual scene. *Perception*, 6(5):529–540, 1977.

[24] B. Riecke. Simple user-generated motion cueing can enhance self-motion perception (vection) in virtual reality. In *Proceedings of the ACM symposium on Virtual reality software and technology*, pages 104–107, 2006.

[25] B. E. Riecke, J. Schulte-Pelkum, F. Caniard, and H. H. Bulthoff. Towards lean and elegant self-motion simulation in virtual reality. In *Proc. IEEE Virtual Reality VR 2005*, pages 131–138.

[26] D. Stewart. A platform with 6 degrees of freedom. In *Proc. of the Institution of Mechanical Engineers*, 1965.

[27] C. W. Stockwell and F. E. Guedry. The effect of semicircular canal stimulation during tilting on the subsequent perception of the visual vertical. *Acta Otolaryngol*, 70(3):170–175, Sep 1970.

[28] S. Tanahashi, H. Ujike, R. Kozawa, and K. Ukai. Effects of visually simulated roll motion on vection and postural stabilization. *J Neuroeng Rehabil*, 4:39, 2007.

[29] L. C. Trutoiu, B. Mohler, J. Schulte-Pelkum, and H. H. Bulthoff. Circular, linear, and curvilinear vection in a large-screen virtual environment with floor projection. In *Proc. IEEE Virtual Reality Conference*, pages 115–120, 8–12 March 2008.

[30] A. Valjamae, P. Larsson, D. Vastfjall, and M. Kleiner. Vibrotactile enhancement of auditory-induced self-motion and spatial presence. *Journal of the Audio Engineering Society*, 54:954–963, 2006.

[31] R. J. van Beers, A. C. Sittig, and J. J. D. van der Gon. How humans combine simultaneous proprioceptive and visual position information. *Exp Brain Res*, 111(2):253–261, Sep 1996.

[32] J. B. F. van Erp, E. L. Groen, J. E. Bos, and H. A. H. C. van Veen. A tactile cockpit instrument supports the control of self-motion during spatial disorientation. *Hum Factors*, 48(2):219–228, 2006.

[33] L. R. Young and M. Shelhamer. Microgravity enhances the relative contribution of visually-induced motion sensation. *Aviat Space Environ Med*, 61(6):525–530, Jun 1990.